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Impacts of Water Temperature on Fall-Run Chinook Salmon *(Oncorhynchus tshawytscha) and* Steelhead *(O. mykiss)* in the San Joaquin River System

Prepared for the:

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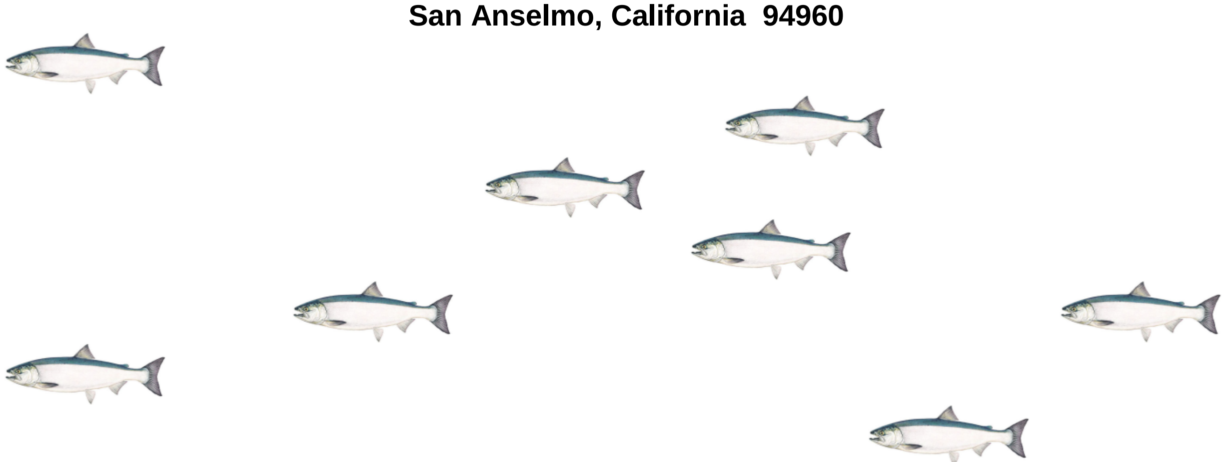

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A.A. RICH AND ASSOCIATES

EXPERT WITNESS STATEMENT OF DR. ALICE A. RICH

I, Dr. Alice A. Rich, declare:

1. I am a fish physiologist, specializing in analyzing the stressful impacts of man-made and natural stressors on fishes, particularly those related to water temperature and pollution on salmon and trout. I received both my Ph.D. and M.S. degrees from the School of Fisheries at the University of Washington in Seattle; both degrees focused on stress physiology of salmon and trout. My B. S. Degree was in zoology from the University of California at Davis. Since 1983, I have owned and managed A. A. Rich and Associates, a fisheries and ecological consulting firm in the San Francisco Bay Area.
2. I was retained by the California Department of Fish and Game to provide the attached expert opinion and testimony (*Impacts of Water Temperature on Fall-Run Chinook Salmon, Oncorhynchus tshawytscha, and Steelhead, O. mykiss, in the San Joaquin River System).*

Alice A. Rich, Ph.D.

Date

I. OBJECTIVES

Staff of the California Regional Water Quality Control Board, Central Valley Region (RWQCB), will hold a public workshop on September 25, 2007, to provide information and receive comments on the potential listing of the Merced, Tuolumne, Stanislaus, and San Joaquin Rivers under the State's Clean Water Act Section 303(d) list as impaired by high water temperature. The California Department of Fish and Game (DFG) will be submitting temperature data and analysis at that workshop. At the request of DFG, my testimony addresses the effects of water temperature on Chinook salmon and steelhead, with regard to the following:

(1) Physiological effects of water temperature on the various life stages of fall-run Chinook salmon and steelhead in the San Joaquin River System; and,

(2) The effects of water temperature-related mortality (both sublethal and lethal) on populations of fall-run Chinook salmon and steelhead in the San Joaquin River System.

II. WATER TEMPERATURE IS ONE OF THE KEY FACTORS THAT HAS RESULTED IN THE DECLINE OF THE CHINOOK SALMON AND STEELHEAD POPULATIONS IN THE SAN JOAQUIN RIVER SYSTEM

The Chinook salmon and steelhead populations in the San Joaquin River System have declined substantially during the past 100 years from a variety of factors, not the least of which have been alterations in water temperatures associated with water impoundments and diversions (Myrick and Cech, 2004). As a result of increased water temperatures, the Chinook salmon and steelhead are each exposed to higher than optimal water temperatures throughout their life cycle. Evidence indicates that these stressful and lethal water temperatures have resulted in reduced egg viability, reduced growth rates, increased rates of disease, higher predation rates, and direct mortality. The long-term result has been a dramatic decrease in populations of these species.

III. PHYSIOLOGICAL CONSIDERATIONS THAT MUST BE ADDRESSED WHEN ANALYZING THE EFFECTS OF WATER TEMPERATURE ON FALL-RUN CHINOOK SALMON AND STEELHEAD

Of all of the life stage requirements of salmon and trout (salmonids), water temperature is the most important, yet, commonly, the least understood. Water temperature can be considered in two ways - as a factor affecting the rate of development, metabolism, and growth, or, as a stressful or lethal factor. The two, of course, are inseparable.

In order to determine, and therefore understand, the thermal effects[1] on Chinook salmon and steelhead, the following physiological and methodological considerations must be addressed:

(1) The inherent complications in the physiological studies used to assess thermal requirements and impacts;

(2) The importance of site-specific thermal physiological studies; and,

(3) The water temperature requirements for each of the life stages of these two species.

A. INHERENT COMPLICATIONS IN THERMAL PHYSIOLOOGY STUDIES

Unfortunately for physiologists and non-physiologists, alike, there is no one methodology used to determine the effects of water temperature on fishes. In fact, to determine the effects of water temperature on fishes, there have been numerous methodologies and, with those methodologies, terms have been defined and used to describe both the type of study and the outcome of the study. The variety of methodologies used to assess thermal impacts on Chinook salmon and steelhead has resulted in a variety of interpretations of the data. The wide variety of responses to water temperature is illustrated at the end of this Testimony (Tables 1 through 11- a summary of what is known about the effects of water temperature on Chinook salmon). The lack of standardized methodologies among fish physiologists has resulted in a variety of definitions for the same term. Similar to all specific areas of scientific inquiry, fish thermal physiology has its own nomenclature which can be confusing when there are different meanings for "optimal", "lethal", "preferred", "tolerance", "threshold", and "stressful" temperatures.

[1] Thermal Effects = any water temperature change that results in modifying physiological functions, including functions that result in thermal stress (e.g., reduced growth, increased disease, increased predation, etc.)

Such a lack of standardization is problematical, when one compares the results of one "optimal temperature" study with that of another, and the results of the former study are based on "thermal tolerance" and those of the latter are based on a disease outbreak. Similarly, the term "lethal" can be used literally, as a percentage of the eggs or fish that die. But the term "lethal" is often also used by physiologists to identify the temperature at which 50% of the eggs or fish die within 28 days, or 7 days, or even 14 hours (Fry et al., 1942) or 12 hours (Brett, 1944), when previously acclimated to the highest possible temperature that will not result in death. In some studies, one counts the number of fish that die and calculates the percentage mortality. In other studies, one estimates mortality, using graphs of water temperature data plotted against the percentage of mortality; this is called either upper or lower incipient lethal. Thus, there are often temperatures below the upper incipient water temperature that are lethal, but that are not necessarily the upper incipient lethal temperature.

To complicate matters further, key factors that affect the outcome of a study include: acclimation temperature; innate metabolic rate; and, environmental conditions, prior to, and during, the experiment (i.e., what other stressors were/are the fish exposed to?). The effects of stress, including thermal stress, are cumulative in Chinook salmon and steelhead (Barton et al., 1986; Jarvi, 1990; Thatcher et al., 1978). Hence, if a fish is under stress from other factors (such as pollution, reduced flows, escaping predators, etc.), adding thermal stress to other stressful factors exacerbates an already stressful situation, and, hence, reduces further the survival potential of the population. Unfortunately for the fish physiologist trying to ascertain the effects of higher than optimal water temperature on salmon and steelhead in the San Joaquin River System, with the exception of direct mortality from lethal water temperatures, the immediate effects are rarely observable. The disorientation that occurs from higher than optimal water temperatures, or a "thermal block" to migration, is rarely observed. For example, the fish may be eaten, thus removing the "evidence". Or, the subsequent decline in egg viability as a result of high water temperatures would only be observed if the adults were tagged and followed into a hatchery and egg viability assessed (Mann and Peer, 2005). However, declining fish populations provide strong evidence that increased water temperatures have contributed overwhelmingly to cumulative physiological stress. In summary, although thermal stress is not easy to ascertain in a non-laboratory environment such as the San Joaquin River System, thermal stress is complicated, cumulative, and has had long-term negative impacts on populations of Chinook salmon and steelhead.

B. IMPORTANCE OF SITE-SPECIFIC DATA

To ascertain the effects of water temperature on Chinook salmon and steelhead populations in the San Joaquin River System, using the results of site-specific data are extremely important. It is evident (Tables 1 through 11) that each study on Chinook salmon and steelhead has its innate set of conditions. Most physiological thermal studies have been conducted under laboratory conditions, where one is able to control the environment, unlike in a river. However, one should be very cautious about making conclusions about the "natural world" from those laboratory studies. In the controlled environment of a laboratory or a hatchery, where fish do not have to escape predators or search for food, no energy is spent on these day-to-day-energy-draining tasks. Furthermore, many of the factors known to affect the outcome of thermal experiments have not been consistently documented. In addition, different geographical areas have different conditions. Hence, one should not assume that the results from a laboratory study or a study conducted in Canada will be the same as those in the San Joaquin River System. Finally, the cumulative effects of stress that fish experience in the wild compound the problems of applying laboratory data to field situations. When a salmonid is under stress in the natural world, adding the stress of high water temperatures for any period of time compounds the problem and, ultimately, reduces the chance of survival and/or being able to successfully reproduce. Thus, to determine the long-term effects of water temperature on Chinook salmon and steelhead in the San Joaquin River Watershed, site-specific thermal physiology studies are essential.

To determine the thermal requirements for juvenile Chinook salmon in the "natural" world, Dr. J.R. Brett, a rather famous Canadian fish physiologist, who conducted some of the most thorough thermal physiology studies on salmon and steelhead, combined laboratory and field studies (Brett et al., 1982). To determine the thermal requirements of the various life stages of Chinook salmon and steelhead, similar studies need to be replicated for the San Joaquin River System. For over 20 years I have provided testimony to the State Water Resources Control Board (Rich, 2007, 2001, 1997, 1987), identifying the types of field/laboratory physiology studies that are needed to determine the optimal water temperatures for Chinook salmon and steelhead. For over 20 years I have observed various fisheries biologists "take" the results of laboratory thermal physiology studies and attempt to use those data to determine thermal requirements for Chinook salmon and steelhead in the "natural" environment of the Central Valley.. It is time to determine the thermal requirements for these species in a site-specific physiologically-sound manner. Until we do such studies, the Chinook salmon and steelhead in the San Joaquin River System will continue to decline to the point that they become extinct.

C. WATER TEMPERATURE REQUIREMENTS FOR CHINOOK SALMON AND STEELHEAD

A physiological optimum is the water temperature under which a number of physiological functions, including growth, swimming, spawning, and heart performance, are optimized (Brett, 1956). Knowledge of temperature tolerance and sublethal stress responses of Chinook salmon and steelhead are far from adequate to define safe thermal limits for Chinook salmon and steelhead in the San Joaquin River System. As there have not been any site-specific bioenergetic thermal studies in the San Joaquin River system for either Chinook salmon or steelhead, it not possible to identify an optimal water temperature range, per se, for each of these species. In addition to the lack of appropriate studies, one of the biggest issues that needs to be resolved is the fact that laboratory studies have demonstrated that optimal water temperatures for both Chinook salmon and steelhead during the parr-smolt transformation were actually lower than those for juvenile rearing. Rearing occurs during the parr-smolt transformation stage. Yet, there are no thermal bioenergetics field studies that specifically identify optimal water temperature for the parr, the juvenile proceeding through smoltification, or the smolt, in a natural river system anywhere. In addition, the optimal thermal range for juvenile Chinook salmon and steelhead depends upon the age of that "juvenile." Thus, the thermal optimal range at that "fry" stage is lower than for the older "juvenile" stage as it is closer to the egg/alevin incubation life stage.

Until site-specific studies are undertaken, one must use the results of previous thermal studies with extreme caution since most of these studies have been hatchery- or laboratory-based studies. Assuming one errs on the side of caution, the thermal optimal ranges are provided as follows.

<u>Chinook Salmon</u>

- Adult Migration and Spawning: 44 °F (6.7 °C) to <59 °F (<15 °C)
- Egg and Alevin Incubation/Fry Emergence: 42.5 °F (5.8 °C) to < 55 °F (13 °C)
- Fry and Juvenile Life Stage: (depends upon how young the fish is):
    - Fry in their first few weeks out of the gravel: 50-55 °F (10 -12.8 °C)
    - Juveniles: 55-60 °F (12.8-15.6 °C)
- Parr-Smolt Transformation: < 56 °F (<13.3 °C)

Steelhead

- Adult Migration and Spawning: 44 to <52 °F (6.7 to < 11.1 °C)
- Egg and Alevin Incubation/Fry Emergence: 46 °F to < 54 F (7.8 - 13 °C)
- Fry and Juvenile Life Stage (depends upon how young the fish is):
    - Fry in their first few weeks out of the gravel: 50-55 °F (10-12.8 °C)
    - Juveniles: < 59 F (<15 °C)
- Parr-Smolt Transformation: < 55 °F (<12.8 °C)

It should be noted that, with the exception of the egg and alevin incubation-to-fry-emergence stage, the thermal optimal ranges for the various life stages are not the same as those reported in EPA's document (EPA, 2003), most notably for the adult migration and egg incubation life stage for Chinook salmon (44-<59 °F) and steelhead (44- < 52 °F), compared to that reported (< 64 °F, < 18°C) in EPA's document. The reasons for these differences are as follows.

Although some fisheries biologists have stated that they believed that the Central Valley salmonids are more tolerant of higher water temperatures than their Pacific Northwest counterparts, there are no data to substantiate that contention. In fact, of the various life stages, the thermal requirements and stressful impacts of higher than optimal water temperatures on the adult life stage of each of these species are the least understood. For adult Chinook salmon and steelhead, one principle governing the criteria for setting safe limits of temperature involves setting acceptable limits for the reduction of such vital functions as reproductive capacity. From the results of the various studies, some of which have been in the Central Valley, thermal stress on Chinook salmon can occur at water temperatures beginning at 59 °F (15 °C); inhibition of the spawning act has been reported to occur at temperatures above 55 °F (12.8 °C); lethal temperatures began at 62.6 °F (17 °C) (Marine, 1992; Ducey, 1986; Ward et al., 2006, 2004). Hence EPA's < 64 °F (< 18°C) for adult migration/egg incubation would, most probably, be extremely stressful and could result in death of Chinook salmon and steelhead in the San Joaquin River System.

In summary, considering the declining population level of Chinook salmon and the Threatened status and relatively rare occurrence of steelhead in the San Joaquin River System, until site-specific thermal bioenergetics studies are undertaken, it is best to err on the side of caution and choose lower thermal optima when the results of laboratory studies provide more than one outcome. For juvenile Chinook salmon and steelhead, the thermal requirements should be differentiated, depending upon whether the fish is a "fry" or very young fish, or an older "juvenile" fish. As the young fish matures, its thermal requirements change, and those changes need to be incorporated into any thermal management decision. Otherwise, it must be assumed that any Chinook salmon or steelhead found outside those thermal requirements are, at a minimum impaired, and, potentially, killed. Thus, adopting higher temperature requirements is rather short-sighted, to say the least, and will contribute further to the decline of these important and sensitive species.

It should also be noted that the thermal optimal ranges for the Chinook salmon and steelhead listed above have no metric associated with them (i.e., minimum, maximum, mean) or duration component. The reason is as follows. For the San Joaquin River System, we do not know what incremental increases in water temperature will result in thermal stress and the extent of that thermal stress. While it is easy to hypothesize about the effects of a "7-day average of daily maximum" water temperature (EPA, 2003), until we know, physiologically, using site-specific studies, we are simply continuing to play "Russian Roulette" with the lives of the Chinook salmon and steelhead in the San Joaquin River System. And, so far, based on the substantial declines in the populations of these species, we are losing that game. It is time to address the thermal issues from a site-specific physiological basis.

IV. PHYSIOLOGICAL EFECTS OF WATER TEMPERATURE ON THE LIFE STAGES OF CENTRAL VALLEY FALL-RUN CHINOOK SALMON AND CENTRAL VALLEY STEELHEAD

Both suboptimal and lethal water temperatures in the San Joaquin River System affect each of the life stages of the Central Valley fall-run Chinook salmon and Central Valley steelhead. Temperature in the rivers fluctuates on a diel basis (i.e., over a 24-hour period). It is often assumed, erroneously, that survival is high if water temperature excursions into the thermal lethal zones are brief. However, studies have illustrated repeatedly the increased mortality risk with increasing water temperatures. Of the various terms used in thermal physiology studies, “thermal stress” is one of the few that is fairly uniformly agreed upon; thermal stress is any temperature change that produces a significant alteration to biological functions of an organism and, hence, lowers the probability of survival (Elliott, 1981).

A. ADULT MIGRATION/EGG INCUBATION/FRY EMERGENCE

Based on studies, both in the Central Valley and elsewhere, during the adult immigration and spawning life stage of Chinook salmon and steelhead, high mortalities, disease outbreaks, and reduced subsequent egg survival can occur at water temperatures equal to or exceeding 59 °F (15 °C). Furthermore, partial blockage to adult fall-run Chinook salmon migration occurred at 66.2 ° F (19 °C) and total migration blockage occurred at temperatures beginning at 69.8° (21 °C) in the San Joaquin River (Hallock et al., 1970). It is generally believed that temperatures beginning at 69.8 ° F (21 °C) will result in total thermal migration blockage to salmon and steelhead (McCullough, 1999).

Delays caused by an unfavorable migration environment may contribute to reproductive failure in the San Joaquin River System. High water temperatures increase the rate at which limited energy is consumed for standard metabolism (Fry, 1971). Completing the act of spawning requires a great amount of stored energy. If a Chinook salmon adult is delayed in spawning for even a few days by any combination of factors (e.g., migration difficulties, migration blockages, or by tributary stream water temperatures that continue to exceed spawning thresholds - approximately 12.8 C), it can be assumed that a large percentage of the adults will not survive to initiate spawning (Andrew and Green, 1960; DeLacy et al., 1956; Paulik, 1960; Gilhousen, 1990). This is based on the bioenergetic assumption that after completing the migration and possibly holding under “normal” thermal regimes, adult females have a limited energy reserve that allows them to excavate a redd and then live a certain number of extra days to guard the redd. If the migration delay subjects females to high holding temperatures in waiting for the thermal blockage to be relieved, at a minimum, valuable energy needed later in spawning (e.g., for redd excavation and defense) is lost, (McCullough, 1999).

B. FRY AND JUVENILE

During the young life of a Chinook salmon or steelhead before it begins its transformation into a marine animal (parr-smolt transformation), higher than optimal water temperatures can result in direct mortality, increased disease rates, reduced growth, and physiological and behavioral changes that jeopardize the fish's existence. At water temperatures above optimum growth boundaries, growth becomes increasingly negative because feeding declines towards zero and the respiration rate increases rapidly. If food becomes limiting (as it usually does at higher water temperatures because the fish cannot obtain enough food to sustain its body functions), the optimum growth zone shifts to a lower water temperatures to compensate for elevated respiration/growth ratios. As a result, in the natural environment, the fish do not grow and can be subject to disease and predation (Elliott, 1981).

Juvenile salmonids exposed to sublethal and lethal water temperatures were selectively preyed upon by larger fishes (Coutant, 1973; Sylvester, 1971; Mesa, 1994). The vulnerability of juvenile salmonids to predation depends on both water temperature and the duration of exposure to high water temperatures (Coutant, 1972). If juvenile salmonids lose equilibrium due to thermal stress or acute thermal shock, their ability to avoid predators can be reduced significantly.

C. PARR-SMOLT TRANSFORMATION AND EMIGRATION

Transformation from parr to smolt during seaward migration for Chinook salmon and steelhead can be blocked by water temperatures in the range 59-68 °F (15-20 °C) and impaired at much lower water temperatues. Water temperatures greater than 62.6 ° (17 °C) place smolts under either lethal or loading stresses that impair metabolic activity, inhibit feeding, and reduce swimming performance. Any or all of these stresses often leads to death (Brett, 1958; Sauter and Maule, 1997; Adams et al., 1973). For steelhead proceeding through the smoltification process, temperatures greater than 55.4 °F (13° C) prevent increases in gill sodium-potassium ATPase activity, a key enzyme involved in the smoltification process (Hoar, 1988). The smolt transformation is inhibited at temperatures exceeding 52.3 °F (11.3 °C) (Adam et al., 1975; Zaugg et al., 1972; Zaugg and Wagner, 1973). In subyearling fall-run Chinook salmon, water temperatures of 64.4-68 °F (18-20 °C) inhibited feeding. In terms of direct mortality, 50% mortality of Chinook salmon smolts in the lower Sacramento River were calculated to have died at temperatures from approximately 71.6-75.2 °F (22-24 °C) (Baker et al., 1995).

In summary, anything that disrupts the parr-smolt transformation, whether it is higher than optimal water temperatures, pollution, or other stressful factors, results in disorientation and can reverse and/or cease the smoltification process. These stressful outcomes can result in making the fish more susceptible to predation, disease and, ultimately, death.

V. EFFECTS OF TEMPERATURE-RELATED MORTALITY ON POPULATIONS OF FALL-RUN CHINOOK SALMON AND STEELHEAD

Although a thermal tolerance study, whose endpoint is death, is easy to undertake and has a specific outcome (i.e., death), sublethal stressful water temperatures can result in a reduction in the population over time. In fact, as stated by an often-quoted fish physiologist, who spent decades studying salmonid physiology, many of those studies focusing on thermal issues,

> ***"Within a population, the inability to maintain near optimum growth at less than optimum temperatures is as decisive to continued survival as more extreme temperatures are to immediate life." (Brett, 1956)***

Less than optimal temperatures become a problem when they impair the fish in some way, such as producing a significant disturbance in the normal functions of the fish, and, thus, decreasing the probability for the fish's survival. Established indicators of thermal stress on Chinook salmon and steelhead migration and spawning, egg incubation, fry emergence, juvenile rearing, and parr-smolt transformation and emigration include: (1) reduced subsequent egg survival; (2) disease outbreaks; (3) growth reduction; (4) reduction in food conversion efficiency; (5) loss of appetite; (6) secretion of stress hormones such as adrenalin; and, (7) hyperactivity (Elliott, 1981; Rich, 1987). All of these stress indicators have been directly and indirectly linked to the reduced survival of natural populations of salmonids. In addition, the stressful impacts of high water temperatures on salmonids are positively related to the duration and severity of the exposure. Thus, the longer the salmon and steelhead are exposed to thermal stress, the less chance there is for long-term survival of the populations as a whole.

In the San Joaquin River System, land use practices (i.e., dams, diversions, pollution, etc.) have led to more rapid water temperature increases in the spring and summer. This has caused water temperatures to exceed 53.6 °F (12 °C) (a critical temperature for initiating smoltification) earlier in the season, compared to historical conditions. Smolting salmonids are either being forced to emigrate earlier than they did historically, to escape warm water conditions in the spring or, as in the case with the steelhead, revert to the parr stage and are being forced to migrate headward to rear in cooler waters and then overwinter a second year. Or, they simply die from the various factors associated with stressful and lethal water temperatures. A rapid warming to the 53.6 °F (12 °C) smoltification threshold may result in less time available for 0+ fall-run Chinook to achieve sufficient size prior to smolting. Small size at smolting may result in a lower percentage of adult returns. In addition, it is quite possible that pre-smolts having low body lipid content or low condition factor, due to their small size at threshold temperatures, cannot sustain further reductions in these factors that would accompany smolt transformation. As result, these fish are less able to tolerate/endure elevated water temperatures as they migrate through the South Delta.

For juvenile Chinook salmon and steelhead in the San Joaquin River System, higher water temperatures actually result in lowering, rather than increasing, the optimal water temperature for growth (as compared to a laboratory situation where the fish can eat all they can consume, it is not bioenergetically possible for a fish in the field to eat maximally). The result: the fish cannot grow because the water temperatures are too high, the fish are preyed upon or become diseased and die. Hence, to manage river temperatures to accommodate the needs of the fry and juveniles before and during the parr-smolt transformation, it is necessary to manage the water temperatures on a watershed (from dam to Delta) basis, so that water temperatures can be maintained in key rearing areas and out-migration corridors.

In terms of lethal temperatures, the ecological consequences can be significant. Juvenile Chinook salmon exposed to heat shock were subject to a significantly greater predation rate than unshocked control fish. Even with a return to the acclimation temperature, increased predation resulted (Coutant, 1973).

VI. SUMMARY

In summary,

(1) Higher than optimal water temperatures are resulting in the reduced long-term survival of both the fall-run Chinook salmon and the steelhead in the San Joaquin River System;

(2) Stressful and lethal water temperatures have resulted in reduced egg viability, reduced growth rates, increased disease, higher predation rates, and direct mortality;

(3) The substantial decline in Chinook salmon and steelhead populations in the San Joaquin River System are due, in large part, to increased water temperatures throughout their life cycles; and,

(4) In order to reverse the trend in the reduced long-term survival of Chinook salmon and steelhead in the San Joaquin River System, it is time to cease using the results of laboratory studies and, instead, conduct long-term, site-specific thermal bioenergetics studies.

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TABLE 1. SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON ADULT CHINOOK SALMON AND DURING SPAWNING MIGRATION

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Impact (s)	Reference
Thermal Tolerance/ Mortality	Spring-run	Adult-Butte Creek Pre-Spawning	≥ 59°F ≥15°C	June 19 to first Week in September	high mortality	Ward et al., 2006, 2004
Thermal Tolerance/ Mortality	Fall-run	Adult-hatchery brood stock	≥ 62.6°F [1] ≥ 17.0 °C	N.P.[2]	high mortality	Ducey, 1986
Thermal Tolerance/ Mortality	Spring-run	Adult-wild Rogue River fish	64.4-69.8 °F 18-21 °C	N.P.[2]	increased mortality	M. Everson (cited by Marine, 1992)
Thermal Tolerance/ Upper Incipient Lethal	Spring-run	Adult	69.8-71.6 °F (fluctuating) [3] 21-22 °C	1 week	upper incipient lethal calculated estimate[4]	Coutant, 1970

[1] In holding ponds at Nimbus Hatchery

[2] N.P. = not provided

[3]Fluctuating = fluctuating water temperature

TABLE 2. SUMMARY OF RESULTS OF THERMAL STRESS STUDIES ON ADULT CHINOOK SALMON DURING THE TIME OF SPAWNING MIGRATION

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Impact (s)	Reference
Thermal Stress/ Avoidance	Fall-run	Adult	65.5, 68.7, 70.3, 74.3°F [1] (lab, constant) ≥74.3 °C	<10 min <10 min.	no avoidance 71-100% avoidance	Weaver, 1968
Thermal Stress/ Avoidance	Fall-run	Adult	>66 °F (field, fluctuating)[1] 18.8 °C	September-November	migration avoidance	Hallock et al., 1970
Thermal Stress/ Handling at high temperatures	Fall-run	Adult-hatchery brook stock	≥59°F [2] (fluctuating)[1] ≥15 °C	N.P. [4]	increased disease incidence	Ducey, 1986
Thermal Stress/ Disease	Spring-run	Adult during spawning migratiion	66.2 °F (fluctuating)[1] 19 °C	1.5 months	increased disease incidence	Berman, 1990 (cited in Marine, 1992)
Thermal Stress/ Egg survival	Fall-run	Adult during spawning migration	59.9-64.4 °F (fluctuating) [3] 15.5-18 °C	migration season	reduced subsequent egg survival	Loudermilk, 1992 (cited by Marine, 1992)

[1] Constant = constant temperatures; Fluctuating = fluctuating temperatures
[2] In the holding ponds at Nimbus Hatchery
[3] Fluctuating = fluctuating water temperature
[4] N.P. = not provided

TABLE 3. SUMMARY OF STUDIES TO DETERMINE OPTIMAL WATER TEMPERATURES ON ADULT CHINOOK SALMON DURING THEIR SPAWNING MIGRATION

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Impact (s)	Reference
Thermal Optimum/ Spawning Preference	Spring-run	Adult Migration and Spawning	43-64.5 °F 6.1-18.1 °C	Spawning Season	Temperatures which exist where migration and spawning occurs	Mattson (1958)
Thermal Optimum/ Spawning Preference	?[1]	Adult Migration and Spawning	42-58 °F 5.6-14.4 °C	Spawning Season	Temperatures which exist where migration and spawning occurs	Burner, 91951)
Thermal Optimum/ Final Preferendum	?[1]	Adult	63.1 °F 17.3 °C	N.P.[2]	Final Prefendum [3] estimate	Spigarelli, 1975 (Cited by Coutant, 1977)

[1]Race of chinook salmon not provided

[2]N.P. = no information provided

[3] Estimated, but unvalidated number

TABLE 4. SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	Fall-run	egg incubation	62 (constant)[1] 65 (constant)[1] 67 (constant)[1]	-------- 31 days 10 days	100 100 100	Seymour, 1952
Thermal Tolerance/ Mortality	Spring-run Fall-run	egg thru early fry[3] egg thru early fry[3]	fluctuating from 60 down to 55 [2] fluctuating from 60 down to 55[2]	1.5 months 6 months	95 75	Johnson and Brice, 1953
Thermal Tolerance/ Mortality	Fall-run (?)[4]	egg thru early fry[3]	62 (constant)[1] 63 (constant)[1] 65 (constant)[1] 67 (constant)[1]	38 days 63 days 63 days 63 days	99 36-98 22-99 25-98	Donaldson, 1955

TABLE 4 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	Fall-run	egg incubation	34 (constant)[1]	100% hatch	100	Seymour, 1956
			39.8, 44.7, 45.2, 46.9, 47, 47.2, 47.4, 50.6, 54.6, 55.1, 57.8, 59 (constant)[1]	50% hatch	1-15	
			59.8, 60.2 (constant)[1]	50% hatch	22-35	
			62, 62.4, 64.6, 64.8, 67 (constant)[1]	50% hatch	78-100	
Thermal Tolerance/ Mortality	Fall-run	egg thru early fry[3]	52.9 (acclimation) to: fluctuating temperatures from 52.9 down to 33 and up to 43[5]	November thru April	7.9	Olson and Foster 1957
			56.9 (acclimation) to: fluctuating temperatures from 56.9 down to 37 and up to 47[5]		16.9	
			59 (acclimation) to: fluctuating temperatures from 59 down to 42 and up to 48[5]		10.3	
			60.9 (acclimation) to: fluctuating temperatures from 60.9 down to 40 and up to 49[5]		10.5	
			65.2 (acclimation) to: fluctuating temperatures from 65.2 down to 42 and up to 51[5]		68	

TABLE 4 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	Fall-run	egg thru early fry[3]	34-38 and >62 (fluctuating)[1] 60-62 (fluctuating)[1] 55-59 (fluctuating)[1] transferred from 60-62 to: 55-56 (constant)[1]	to eyed stage	100 50 20 70	Hinze, 1959
Thermal Tolerance/ Mortality	Fall-run (?)[4]	egg incubation	34.6, 35.1,37.4 (constant)[1] 39.9, 40.1, 42.4, 42.6, 44.7, 44.7, 47.4, 49.2, 54.9, 57.5, 59.5 (constant)[1] 34.9, 37.3 (constant)[1] 40, 42.5, 44.9 (constant)[1]	N.P.[6]	100, 99.6, 52.6 0.7-18.5 30.9-98.7 0.9-10.2	Combs and Burrows, 1957
Thermal Tolerance/ Mortality	Fall-run (?)[4]	egg incubation	42.5 (constant)[1]	< 1 hour	92	Combs, 1965

TABLE 4 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	Winter-run	egg thru early fry[3]	45.7, 47.3, 48.5, 53.9 (mean temperatures)[5]	May-January	1.1-4.3	Slater, 1963
			50 (constant)[1]	N.P.[6]	5.0	
			56.5, 57.1, 59.4 (mean temperatures)[5]	May-January	11.1-13.6	
			59.7, 63.3 (mean temperatures)[5]	May-January	49.1-97.6	
Thermal Tolerance/ Mortality	? [4]	egg incubation	42.5 (constant)[1]	< 1 hour	92	Combs, 1965
Thermal Tolerance/ Mortality	Fall-run	egg incubation	50-62 (fluctuating)[1]	2 - 3.5 months	27-35	Healey, 1979
		egg incubation	60-61 (fluctuating)[1]	2 months	33	
		egg thru early fry[3]	50-58 (fluctuating)[1]	2 months	6-9	
		egg thru early fry[3]	44-60 (fluctuating)[1]	2 - 3.5 months	3-13	
Thermal Tolerance/ Mortality	?[4]	egg incubation	42.8, 46.4, 50 (constant)[1]	thru emergence	1.2-4.1	Heming, 1982
			53.6 (constant)[1]		11.6	

TABLE 4 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	?[4]	egg thru early fry[3]	50.9 (50.7-51.8) [8] 53.6 (53.4-54.1) [8] 56.3 (55.9-56.8) [8] 59 (58.6-59.9) [8]	66 days 118 days 115 days 81 days	0-8 7-23 33-90 85-100	Eddy, 1971
Thermal Tolerance/ Mortality	?[4]	egg to swim-up stage egg to swim-up stage egg to swim-up stage	52.5 ± 0.7 [7] 49.8 ± 0.7 [7] 59.2 ± 1.4 [7]	128 days 128 days 128 days	51 ± 27 [7] 50 ± 27 [7] 77 ± 20 [7]	Garling and Masterson, 1985
Thermal Tolerance/ Shock Mortality	?[4]	eggs and alevins	transfer from 50 to: 71.7 74.3 77.0 79.7	1-8 hours	 100 100 100 100	Neitzel and Becker, 1985
Thermal Tolerance	?[4]	egg thru fry emergence	35.6 and 57.2 (constant) [1]	thru hatching	increased mortalities	Murray and McPhail, 1988

TABLE 4 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON FROM EGG INCUBATION THROUGH FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance	Winter-run	egg thru fry emergence	>58 constant	thru hatching	increased mortalities	Johnson, 1997

[1] Constant = constant temperature; Fluctuating = fluctuating temperatures in a flow-thru system, usually to river at hatchery.

[2] Mean daily fluctuating temperatures, with maximum of 60 °F at beginning and down to 55 °F by the end of the experiment.

[3] In determining percent mortality, as a function of water temperature, no differentiation was made between eggs, alevins, or fry.

[4] Did not provide any information on the race of chinook salmon

[5] Mean daily fluctuating temperatures, in flow-thru system to river at hatchery, with lowest temperatures in the winter

[6] Not provided

[7] Mean ± standard deviation

[8] Mean during course of experiment (range of water temperatures)

TABLE 5. SUMMARY OF RESULTS OF THERMAL STRESS STUDIES ON CHINOOK SALMON FRY AND JUVENILES FROM EGG INCUBATION THRU FRY EMERGENCE

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Impact (s)	Reference
Thermal Stress/ Disease	Fall-run	egg thru early fry[1]	63, 65, 67 (constant) [2, 3,]	63 days	increased disease incidence	Donaldson, 1955
Thermal Stress/ Development	?[4]	egg incubation	< 35.6 and >57.2		no development	Murray and McPhail, 1988
Thermal Stress/ Bone Deformities	Fall-run	egg thru early fry[1]	≤ 40 and ≥ 60 [3]	46 weeks	abnormal vertebrae	Seymour, 1956

[1] In determining disease, as a function of water temperature, no differentiation was made between eggs, alevins, or fry

[2] Constant = constant temperatures; Fluctuating = fluctuating temperatures in a flow-thru system, usually to a river at hatchery

[3] Fed Maximal Rations

TABLE 6. SUMMARY OF RESULTS OF STUDIES TO DETERMINE OPTIMAL WATER TEMPERATURES DURING THE EGG THRU FRY EMERGENCE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Impact (s)	Reference
Thermal Optimum	Fall-run	egg incubation	39.8-59 (constant)[1]	46 weeks	thermal optimum[2]	Seymour, 1956

[1]Constant = constant temperature

[2] Seymour's (1956) conclusion, based on results of his mortality and stress studies

TABLE 7. SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Lethal Minimum[1]	Spring-run	juvenile	45.3 (acclimated to 73.4)	approx. 3.5 days	50 (calculated estimate)	Brett, 1952
Thermal Tolerance/ Upper Incipient Lethal Temperature[2]	Spring-run	juvenile	77.2 ± 0.2[6]	approx. 10 hours	50 (calculated estimate)	Brett, 1952
Thermal Tolerance/ Lethal Maximum[1]	Spring-run	juvenile	76.5 (calculated estimate)	28 days	50 (calculated estimate)	Brett et al., 1982
Thermal Tolerance/ Mortality	Spring-run	juvenile	76.1-78.8 (acclimated to 50)	28 days	100	Brett et al., 1982
Thermal Tolerance/ Mortality	Spring-run Fall-run	egg thru early fry[3] egg thru early fry[3]	fluctuating from 60 down to 55[9] fluctuating from 60 down to 55[9]	1.5 months 6 months	95 75	Johnson and Brice, 1953
Thermal Tolerance/ Mortality	Spring-run	juvenile	32 (constant)[11]		100	Brett, 1952
Thermal Tolerance/ Mortality	(?)[10]	egg thru early fry[3]	62 (constant)[11] 62 (constant)[11] 62 (constant)[11] 62 (constant)[11]	38 days 63 days 63 days 63 days	99 36-98 22-99 25-98	Donaldson, 1955

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	Fall-run	egg thru early fry[3]	52.9 (acclimation) to: fluctuating temperatures from 52.9 down to 33 and up to 43 [12] 56.9 (acclimation) to: fluctuating temperatures from 56.9 down to 37 and up to 47 [12] 59 (acclimation) to: fluctuating temperatures from 59 down to 42 and up to 48 [12] 60.9 (acclimation) to: fluctuating temperatures from 60.9 down to 40 and up to 49 [12] 65.2 (acclimation) to: fluctuating temperatures from 65.2 down to 42 and up to 51 [12]		7.9 16.9 10.3 10.5 68	Olson and Foster 1957
Thermal Tolerance/ Mortality	Fall-run	egg thru early fry[3]	34 - 38 and >62.1 (fluctuating)[11] 60 - 62 (fluctuating)[11] 55 - 59 (fluctuating)[11] transferred from 60-62 to: 55-56 (constant)[11]	to eyed stage	100 50 20 70	Hinze, 1959

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Tolerance/ Mortality	?[3]	egg thru early fry[3]	50.9 (50.7-51.8)[8] (constant)[11] 53.6 (53.4-54.1)[8] (constant)[11] 56.3 (55.9-56.8)[8] (constant)[11] 5.9 (58.6-59.9)[8] (constant)[11]	66 days 118 days 115 days 81 days	0-8 7-23 33-90 85-100	Eddy, 1971
Thermal Tolerance/ Mortality	Spring-run	juveniles	≤ 49[13] (constant)[11] 54, 59, 64, 68, .9, 73.9 (constant)[11, 13]	25 days	2-6 20,31,52,70,92	Holt et al., 1975
Thermal Tolerance/ Mortality	Spring-run	juveniles	39 (constant)[11, 14] 44.1, 48.9, 54, 59, 64, 68.9 (constant)[11, 14]	25 days	8 26, 48, 70, 56, 74, 93	Groberg et al., 1978
Thermal Tolerance/ Mortality	Fall-run	early fry	50-62 (constant)[11] 60-61 (constant)[11]	2 - 3.5 months 2 months	50--55 47	Healey, 1979
Thermal Tolerance/ Mortality	Spring-run	juvenile	76.6 ± 0.7 (constant)[11]	28	64	Brett et al., 1982
Thermal Tolerance/ Mortality	Fall-run	juveniles	69.8 (constant)[11]	24 hours	increased mortality	Barton and Schreck, 1987
Thermal Tolerance/ Mortality	Fall-run	juvenile	75.2 ± 1.9[6] (constant)[11]	33 days	100	Rich, 1987

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Percent Mortality	Reference
Thermal Shock	Fall-run	juveniles-yoy[4, 7]	Transferred from 55 F to: 60, 65,69,and 73 F	6 minutes	0	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[4, 7]	Transferred from 60 F to: 60, 65,70 and 74 F	6 minutes	5	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[4, 7]	Transferred from 60 F to: 60,65,and 70 F 75 F 80 F 85 F	24 hours	0 4 95 100	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 60 F to: 60 F 65and 70 F 75 F 80 F 85 F	24 hours	10 0 50 90 100	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[6, 7]	Transferred from 60 F to: 60 F 70 F 75 F 77 F 80 F	48 hours	10 0 80 90 100	Orsi, 1971

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Percent Mortality	Reference
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 65 F to: 65 F 70 F 75 F 79 F 83 F	6 minutes	 30 40 60 10 40	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 65 F to: 65,70,72 F 75 F 77 F 80 F	24 hours	 0 10 90 100	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 65 F to: 65,70,72 F 75 F 77 F 80 F	48 hours	 0 20 10 100	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 70 F to 70 F 75 F 80 F 84 F 88 F	6 minutes	 10 20 0 10 100	Orsi, 1971

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Percent Mortality	Reference
Thermal Shock	Fall-run	juveniles-yoy[4, 7]	Transferred from 70 F to 70 F 72 F 75 F 77 F 80 F	24 hours	 23-35 0-70 10-100 55-100 100	Orsi, 1971
Thermal Shock	Fall-run	juveniles-yoy[5, 7]	Transferred from 70 F to 70 F 72 F 75 F 77 F 80 F	48 hours	 50-100 20-95 55-100 100 100	Orsi, 1971

TABLE 7 (CONT.). SUMMARY OF RESULTS OF THERMAL TOLERANCE STUDIES ON CHINOOK SALMON DURING THE FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Percent Mortality	Reference
Thermal Shock/ Predation	**?[10]**	**Juveniles**	**78.8, 82.4, 86 (constant)[11]**	**variable**	**Significantly increase in being preyed upon**	**Coutant, 1973**

[1] temperature causing 50% death (LT50) in 28 days; this is a mathematically calculated estimate
[2] Upper Incipient Lethal Temperature: the temperature causing 50% death (LT50) in 28 days at an acclimation temperature of 76.1° F; this is a mathematically calculated estimate
[3] In determining percent mortality, researchers did not differentiate between eggs, alevins, and early fry stage.
[4] yoy = young-of-the-year; hatchery fish used for experiments
[5] yoy = young-of-the-year; fish which had been collected in field for the experiments
[6] mean ± standard error of the mean
[7] fish fed maximal food rations
[8] mean temperatures during course of experiment (range of water temperatures)
[9] mean daily fluctuating temperatures, with maximum of 60 °F at beginning and down to 55 °F by the end of the experiment
[10] study did not provide any information on race of chinook salmon
[11] constant= constant temperature; Fluctuating = fluctuating temperatures in a flow-thru system, usually to river at hatchery
[12] mean daily fluctuating temperatures, in flow-thru system to river at hatchery, with lowest temperatures in the winter
[13] fish were infected first with *F. columnaris*, then exposed to various constant temperatures, thus this is a cumulative stress response
[14] fish were infected first with *Aeromonas*, then exposed to various constant temperatures, thus this is a cumulative stress response

TABLE 8. SUMMARY OF RESULTS OF THERMAL STRESS STUDIES ON CHINOOK SALMON FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Impact (s)	Reference
Thermal Stress/ Disease	Fall-run	egg thru early fry[1]	63, 65, 67 (constant) [2, 3]	63 days	increased disease incidence	Donaldson, 1955
Thermal Stress/ Disease	? [4]	juveniles	63, 64 (constant) [2, 3]	20 weeks	increased mortality associated with disease	Fujihara et al., 1971
Thermal Stress/ Bioenergetics	? [4]	juveniles	65 (constant) [2, 3]	4 weeks	reduced growth rate	Banks et al., 1971
ThermalStress/ Bioenergetics	Spring-run	juveniles	7.2 °F higher than control for one year (Fluctuating) [5] 48.0 ± 5.0 to 67.6 ± 3.0 48.6 ± 3.6 to 66.9 ± 3 .6	one year for each of two groups of fish	reduced (30-50%) production[6] reduced growth efficiency [6] reduced biomass of food organisms[6]	Bisson and Davis, 1976
Thermal Stress/ Bioenergetics	Spring-run	juveniles	70.5 (constant) [2, 3]	28 days	no growth reduced food conversion efficiency	Brett et al., 1982
Thermal Stress/ Bioenergetics	Spring-run	juveniles	64.6-66.2 (constant) [2, 3]	28 days	20% reduction in growth rate	Brett et al., 1982
Thermal Stress/ Bioenergetics	Fall-run	juveniles	≥66.2 ±.1.4 constant) [2, 3]	28 days	reduced growth rate [6] reduced food conversion efficiency[6] increased incidence of disease reduced appetite	Rich, 1987
Thermal Stress/ Avoidance	? [4]	juveniles	transferred from 55.4 to 62.6		75% avoidance	Gray et al., 1977

TABLE 8 (CONT). SUMMARY OF RESULTS OF THERMAL STRESS STUDIES ON CHINOOK SALMON FRY AND JUVENILE LIFE STAGES

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Impact (s)	Reference
Thermal Stress/ Carbohydrate and internal response	Fall-run	juveniles	69.8 (constant)[1]	24 hours	increased glucose concentration increased rate of cortisol secretion	Barton and Schreck, 1987

[1] In determining disease, as a function of water temperature, no differentiation was made between eggs, alevins, or fry

[2] Constant = constant temperatures; Fluctuating = fluctuating temperatures in a flow-thru system, usually to a river at hatchery

[3] Fed Maximal Rations

[4] Did not provide any information on race of chinook salmon

[5] A model stream experiment with a fluctuating, flow-thru system. The unheated (control) temperatures ranged from 39 ± 8.5 °F to 61.7 ± 3 °F and the heated (experimental) temperatures ranged from 48 ± 5 °F to 67.6 ± 3 °F for the first year. For the second year (second group of fish), the unheated (control) temperatures ranged from 42 ± 3.4 °F to 59.9 ± 2.9 °F and the heated (experimental) temperatures ranged from 48.6 ± 3.6 °F to 66.9 ± 3 .6 °F

[6] Statistically significant ($p < 0.05$)

TABLE 9. SUMMARY OF RESULTS OF STUDIES TO DETERMINE OPTIMAL WATER TEMPERATURES ON FRY AND JUVENILE CHINOOK SALMON

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Result (s)	Reference
Thermal Preference	Spring-run	"fingerling"	53.6-55.4 (acclimation temperature 68)	N.P.[8]	Preferred Temperature	Brett, 1952
Thermal Preference/ "Final Preferendum)	Spring-run	juvenile	53.1	N.P.[8]	"Final Preferendum"	Brett, 1952
Thermal Optimum/ Growth Rate	Fall-run	fry	55[2] 60[2]	N.P.[7] N.P.[7]	Maximum growth Maximum growth	Seymour, 1956
Thermal Optimum/ Growth Rate	?[1]	juvenile	60[2]	4 weeks	Maximum growth	Banks et al., 1971
Thermal Optimum/ Growth Rate	Spring-run	juvenile	64.6 - 69.6[2]	28 days	Maximum growth	Brett et al., 1982
Thermal Optimum/ Growth Rate	Fall-run	juvenile	55.8 ± 0.4 - 59.5 ± 0.9 [2, 3]	33 days	Maximum growth	Rich, 1987
Thermal Optimum/ Food Conversion Efficiency	Fall-run	juvenile	55.8 ± 0.4 - 59.5 ± 0.9 [2, 3]	33 days	Maximum Food Conversion Efficiency	Rich, 1987
Thermal Optimum	Fall-run	fry	58[2]	N.P.[7]	Thermal Optimum estimated (lab)	Seymour, 1956
Thermal Optimum	?[1]	fry	53.6	thru early fry	Thermal Optimum estimated (lab)	Heming et al., 1982

TABLE 9 (CONT.). SUMMARY OF RESULTS OF STUDIES TO DETERMINE OPTIMAL WATER TEMPERATURES ON FRY AND JUVENILE CHINOOK SALMON

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Result (s)	Reference
Thermal Optimum	Spring-run	juvenile	66.2[2, 4]	28 days	Thermal Optimum estimated (lab)	Brett et al., 1982
Thermal Optimum	Spring-run	juvenile	58.6 [5, 6]	28 days	Thermal Optimum estimated (field)	Brett et al., 1982
Thermal	Fall-run	juvenile	58-61[2]	33 days	Thermal Optimal Range estimated (lab)	Rich, 1987

[1] did not provide any information on race of chinook salmon

[2] fish fed Maximal Rations

[3] mean ± standard error of the mean

[4] calculated estimate (unvalidated)

[5] fish estimated (unvalidated) to have fed on 60% Maximal Ration

[6] calculated estimate (unvalidated)

[7] N.P. = not provided

TABLE 10. SUMMARY OF RESULTS OF THERMAL STRESS STUDIES ON CHINOOK SALMON DURING THE PARR-SMOLT TRANSFORMATION

Type of Experiment	Race/Run	Life Stage	Temperature (°F)	Duration of Exposure	Impact (s)	Reference
Thermal Stress	Fall-run	juvenile parr-smolt	≥ 49.5[1, 2]	6-7 months	reduced growth rate	Clarke and Shelbourne, 1985
Thermal Stress	Fall-run	juvenile parr-smolt	56.8[1, 2]	6-7 months	osmoregulatory stress	Clarke and Shelbourne, 1985

[1] Fed Maximal Food Rations

[2] Fish were transferred from freshwater tanks (water temperatures in the tanks ranged from 44.4-62.8 °F) to seawater tanks (water temperatures ranged from 48.0-58.3 °F); temperatures which are listed in the table above were from freshwater data.

TABLE 11. SUMMARY OF STUDIES TO DETERMINE OPTIMAL WATER TEMPERATURES ON CHINOOK SALMON THE PARR-SMOLT TRANSFORMATION

Type of Experiment	Race/Run	Life Stage	Temperature	Duration of Exposure	Impact (s)	Reference
Thermal Optimum/ Maximum Growth	Fall-run	parr-smolt	transferred from freshwater (at 49.5) to seawater (at 57.4)[1, 2]	6-7 months	Maximum growth	Clarke and Shelbourne, 1985
Thermal Optimum/ Maximum Growth	Fall-run	parr-smolt	transferred from freshwater (at 49.5) to seawater (at 57.4)[1, 2]	6-7 months	Optimal potassium sodium regulation	Clarke and Shelbourne, 1985

[1]Fed Maximal Ration

[2]Fish were transferred from freshwater tanks (water temperatures in the tanks ranged from 44.4-62.8 °F) to seawater tanks (water temperatures in the tanks ranged from 48-58.3 °F); temperatures that are listed in the table above were from freshwater studies.